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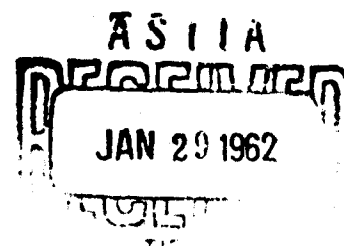
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EFFECTS OF MODERATELY HIGH STRAIN RATES ON
THE TENSILE PROPERTIES OF METALS

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EFFECTS OF MODERATELY HIGH STRAIN RATES ON THE TENSILE PROPERTIES OF METALS

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INTRODUCTION

Since the release of DMIC Memorandum 4 on "Effects of High Strain Rates and Rapid Heating on the Tensile Properties of Titanium Alloys", a number of inquiries have been received by DMIC on the effects of high strain rates on other metals and alloys. Because of the general interest, this memorandum has been prepared to show typical effects of increasing the strain rate to nearly 100 inches per inch per minute at room and elevated temperatures on the tensile properties of a number of commercial alloys. More complete information on specific effects of moderately high strain rates on these and other alloys can be obtained by referring to reports listed in the Bibliography.

Many investigators have reported on plastic wave phenomena during exceedingly rapid straining. The loading rates required to produce these phenomena fall into the range of impact tests and are beyond the attempted scope of this memorandum. The works of D. S. Clark** (12-16, 20-22) and others are suggested as sources of information on tensile impact properties.

The discussion and data presented in this memorandum also supplement DMIC Report 130 on "Selected Short-Time Tensile and Creep Data Obtained Under Conditions of Rapid Heating".

EFFECTS OF MODERATELY HIGH STRAIN RATES ON TENSILE PROPERTIES

Increasing the rate of straining during tensile testing is synonymous with increasing the rate of load application. The straining rate and loading rate are proportional up to the elastic limit of the test material. In actual service, it is the rapid application of loads that causes rapid straining. The primary reason for referring to constant strain rates is that, with screw-driven testing machines, relatively constant strain rates are readily obtained with a constant-speed drive mechanism.

In order to show the effects of increasing strain rates, typical tensile-test data are plotted according to stress versus strain rate for tests at room temperature and at elevated temperatures. Plots of typical data for a number of commercial alloys discussed in later sections of this memorandum illustrate the following general trends resulting from increasing the strain rate:

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**Numbers in parentheses refer to references in the Bibliography.

- (1) When testing at room temperature, the yield and ultimate tensile strengths of a given alloy either are not affected or are increased slightly as the strain rate is increased.
- (2) When testing at slightly elevated temperatures, the effect of increasing the strain rate is generally similar to that at room temperature, if the alloy has negligible tendency to creep at stresses lower than the yield strength and remains in a stable condition. However, the yield and ultimate strengths are usually lower, dependent on the temperature. Under these conditions, the length of time at which the specimen is maintained at the testing temperature before it is loaded has little effect on its strength.
- (3) When testing at high temperatures, increasing the strain rate causes substantial increases in the yield and ultimate strengths, if the alloy tends to creep at stresses lower than the yield strength. As the testing temperature is increased, the yield and ultimate strengths of a given alloy tend to coincide.
- (4) The elastic modulus of a given alloy at a given testing temperature is relatively constant regardless of strain rate.
- (5) Effects of strain rate on ductility are not consistent.
- (6) Reactions which change the structure of the alloy will affect the properties of the alloy when it is heated to a temperature at which the reaction can proceed. These reactions may be precipitation hardening, strain aging, overaging, tempering, recrystallization, and grain growth, or other reactions or combinations of them.

In order to determine how these factors affect the properties of current engineering alloys, a number of testing programs have been initiated. Results of some of these programs are shown in the following sections. Most of this work has been done on sheet specimens with test sections 1/2 inch wide and 2 inches long.

For the data presented in the tables, the specimens that were heated to temperature in 10 or 20 seconds were heated by self-resistance, that is, by passing a controlled electric current through the specimen being tested. In most instances where data for several holding times were available, only data for the shortest holding time (10 seconds) are reported for the rapidly heated specimens. The specimens that were heated to temperature over a period of 15 or 30 minutes were heated by radiation. All strain rates were converted to in./in./min for uniformity in presentation.

Aluminum Alloys

Results of tensile tests on three sheet aluminum alloys at strain rates of about 0.003 in./in./min. to 60 in./in./min. and from room temperature to 600 F are shown in Figures 1 to 3. It will be noted that the yield and ultimate strengths at room temperature for the 2014-T6 alloy in Figure 1 were only slightly affected by wide variations in strain rate. For tests made at the standard rate of 0.003 in./in./min, increasing the testing temperature to 600 F resulted in decreasing yield and ultimate strengths to about 12,000 psi. When tested at a strain rate of about 60 in./in./min, however, the yield strength was 30,000 psi at 600 F. Thus a substantial gain in strength was obtained at 600 F under conditions of rapid straining. The curves in Figure 1 also show the tendency for the yield and ultimate strengths to occur at nearly the same stress levels under conditions representative of relatively high-temperature behavior for the alloy.

The tensile data for 2024-T3 aluminum alloy in Figure 2 show the effect of precipitation hardening at 450 F during testing. The yield strength at 450 F was higher at a strain rate of 0.003 in./in./min than it was at the higher strain rates. At the low strain rate, there was sufficient time during testing for precipitation hardening to occur before the yield strength was reached. Because of the shorter time required for testing at the higher strain rates, the precipitation-hardening effect on the yield strength was less prominent. At 600 F the specimens had overaged; however, in these specimens, considerably higher strengths were obtained at the higher strain rates.

The effect of increased strain rates for 7075-T6 sheet aluminum alloy is shown in Figure 3. The same trends are noted for this alloy as for 2014-T6 (Figure 1).

Beryllium

Because of its excellent heat-sink characteristics, its relatively light weight, and its high modulus, beryllium has been considered for certain applications which must withstand aerodynamic heating. Such components are often subjected to rapid straining and rapid heating. Preliminary data as reported by Preston and Kattus(57) on the effect of rapid straining of beryllium bar at room and elevated temperatures are presented in Figure 4.

The room-temperature tensile strength at the fastest strain rate (20 in./in./min) is relatively low, probably because of the brittleness of the material. At this strain rate, the room-temperature strength is about the same as the strength at 1500 F. At 1000 and 1500 F the specimens had 4.5 and 3.0 per cent elongation, respectively, at the highest strain rate. The properties of beryllium appear to be more attractive at elevated temperatures than at room temperature.

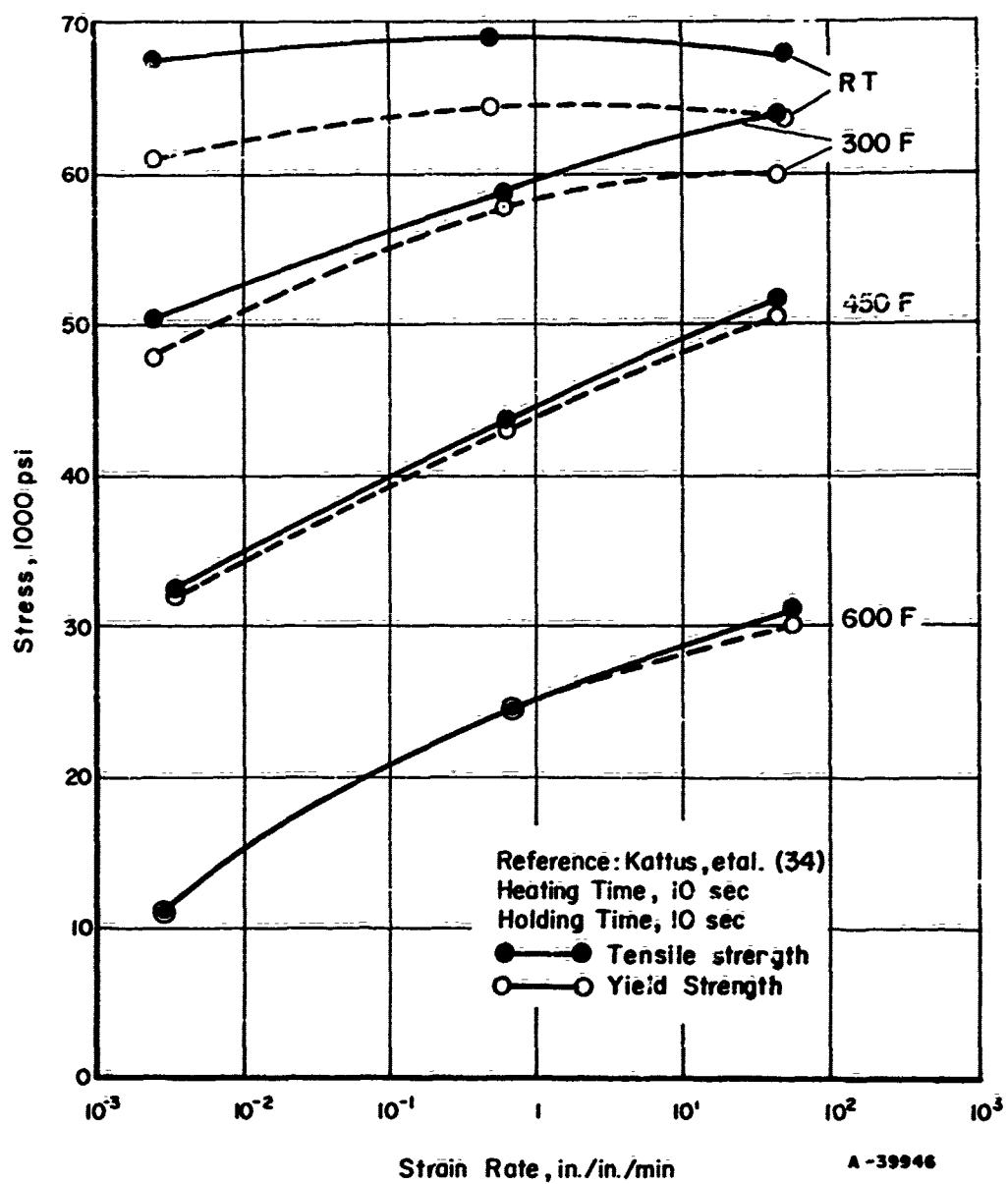


FIGURE 1. ALCLAD 2014-T6 ALUMINUM ALLOY SHEET,
 TRANSVERSE SPECIMENS, 0.064-INCH THICK

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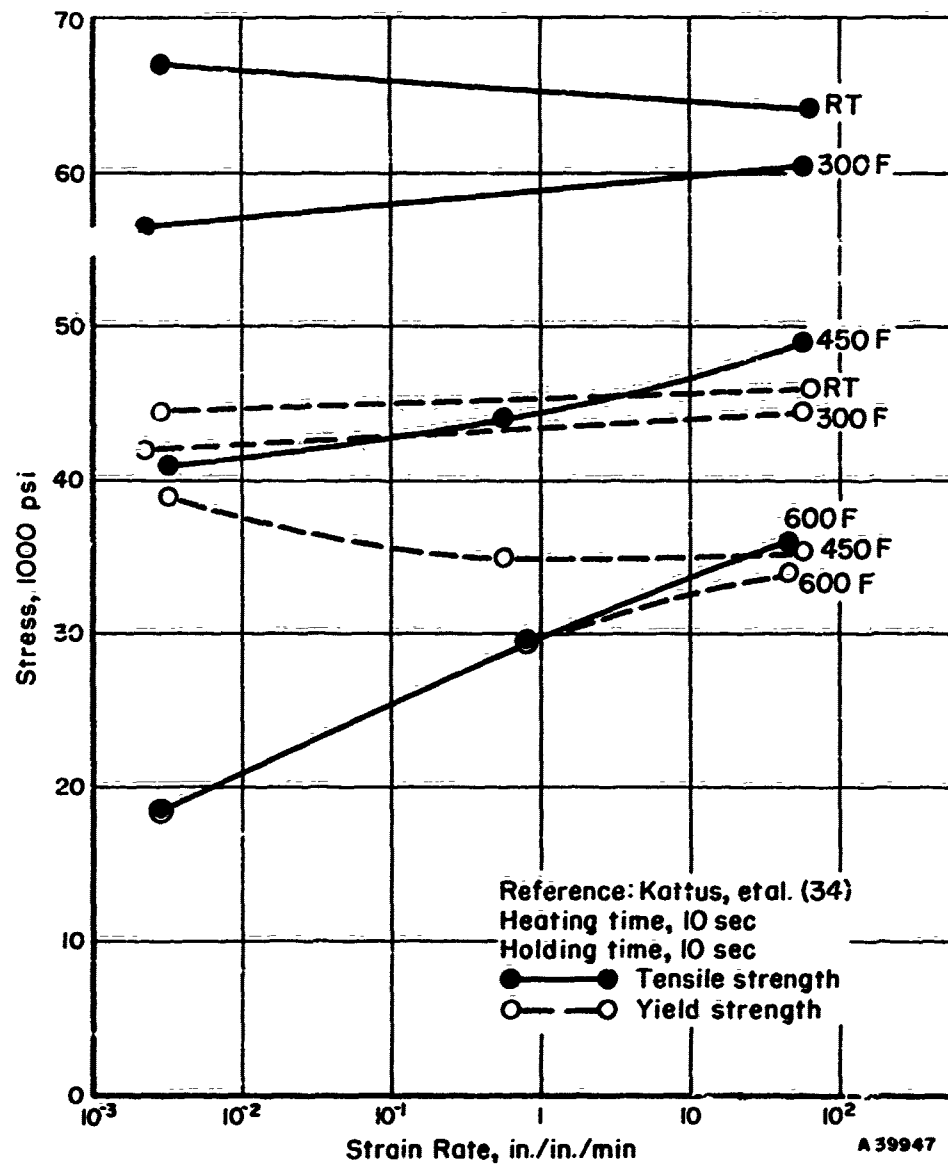


FIGURE 2. ALCLAD 2024-T3 ALUMINUM ALLOY SHEET,
 TRANSVERSE SPECIMENS, 0.054-INCH THICK

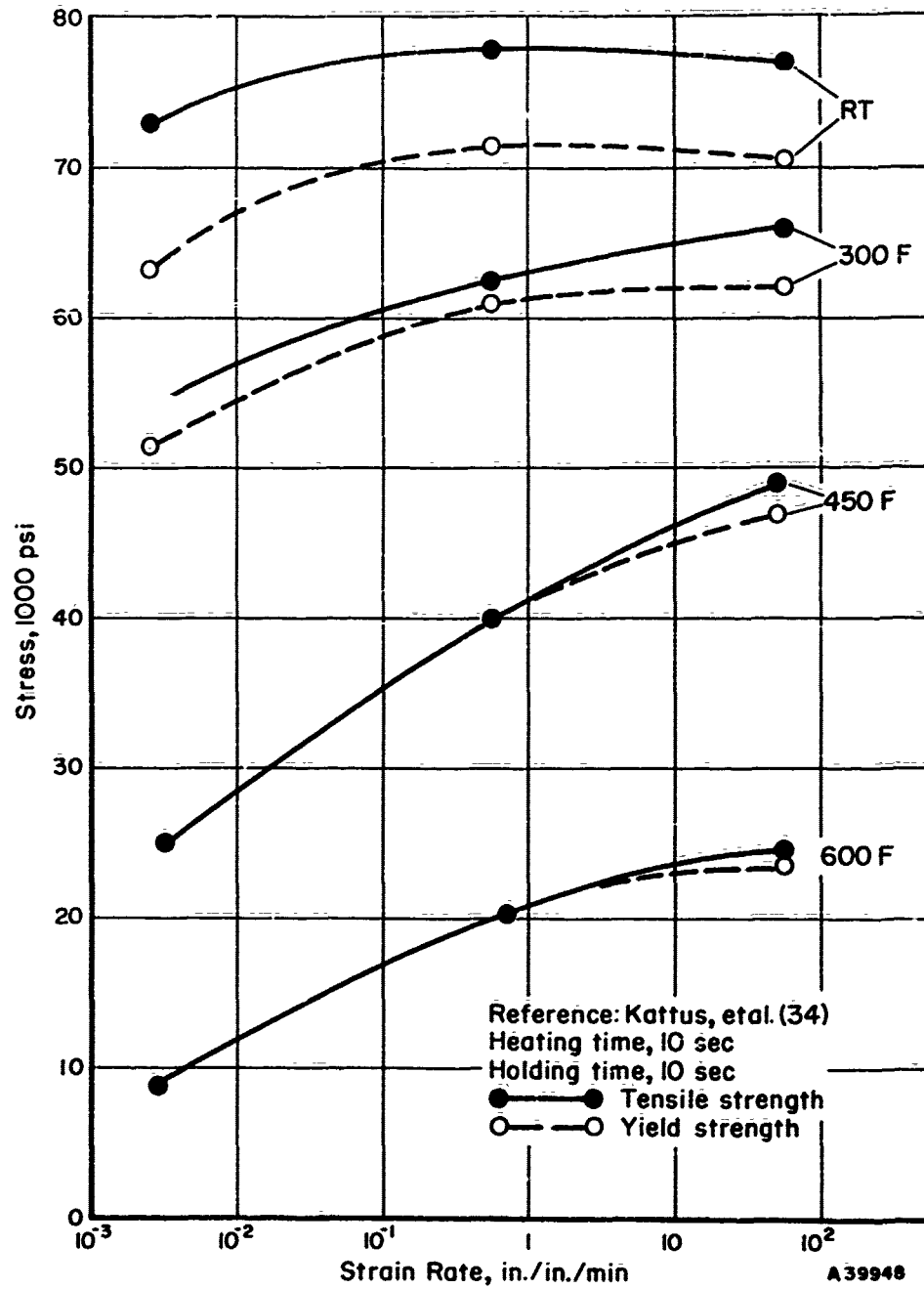


FIGURE 3. ALCLAD 7075-T6 ALUMINUM ALLOY SHEET,
 TRANSVERSE SPECIMENS, 0.064-INCH THICK

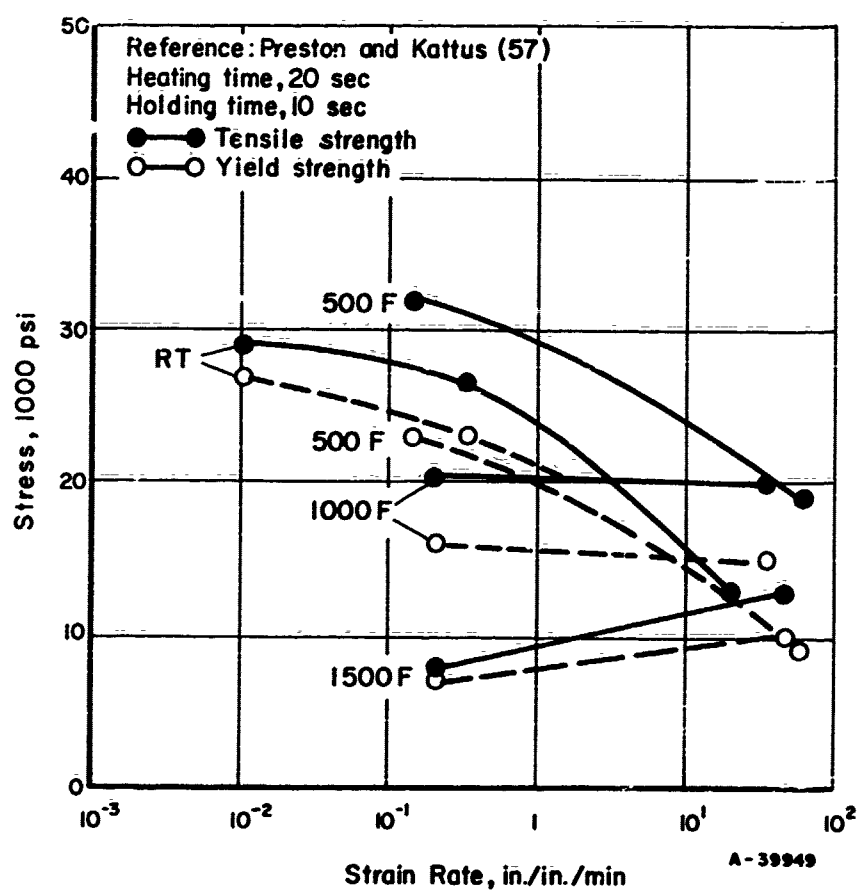


FIGURE 4. UNALLOYED BERYLLIUM BAR TESTED IN ARGON

Low Alloy Steel

Results of tensile tests over a wide range of strain rates are shown for normalized AISI 4130 steel sheet in Figure 5 and for quenched-and-tempered 4130 steel sheet in Figure 6. The general trends for effects of increasing the strain rate at room and elevated temperatures, as discussed previously, are valid for this and similar steels.

However, when the testing temperature exceeds the tempering temperature, the strength will be decreased as a result of the tempering effect. This reaction is dependent both on temperature and on time, but for this steel, varying the holding times from 10 to 1,800 seconds had little effect on the strengths at each of the strain rates. Therefore, the tempering effect must occur within the shortest holding time (10 seconds). Furthermore, for the 4130 steel, the increase in strength with increased strain rates at 1200 F is primarily an effect of the strain rate, per se. When the tempering effect occurs at a slower rate than in the 4130 steel, rapid heating and straining could occur before the material becomes stabilized (when the maximum temperature is above the tempering temperature). In this case, higher strengths would be obtained.

Hot-Work Die Steels

Because of the high strengths that can be achieved, hot work die steels are being considered for a number of highly stressed airborne components. These steels also retain considerable strength at elevated temperatures. The data plotted in Figures 7 and 8 are for two of the hot-work die steels tempered at 950 F. It will be noted that yield strengths of about 150,000 psi were obtained at 1200 F at strain rates of about 30 in./in./min with holding times of 10 seconds. Holding times of 30 minutes at 1200 F resulted in considerably lower strengths than with the short holding times. Apparently, the tempering reaction for these steels requires considerable time at 1200 F. Therefore, if service temperatures exceed the tempering temperature but are attained rapidly and if the component is loaded rapidly, it will withstand considerably higher stresses for a short period of time than would be possible with longer heating times.

Austenitic and Heat-Treatable Stainless Steels

Results of tensile tests over a wide range of strain rates for representative stainless steels are shown in Figures 9 to 13. The plotted data in Figure 9 show that annealed Type 301 stainless steel is not strain-rate sensitive until a testing temperature of about 1500 F is reached. At this temperature, the ultimate strength is increased as the strain rate is increased, although the yield strength is not affected by the strain rate.

The curves in Figure 10 are for full-hard Type 301 stainless steel. Data for the full-hard alloy were not obtained at the same temperatures as for the annealed alloy, but a comparison of the data in Figures 9 and 10 will

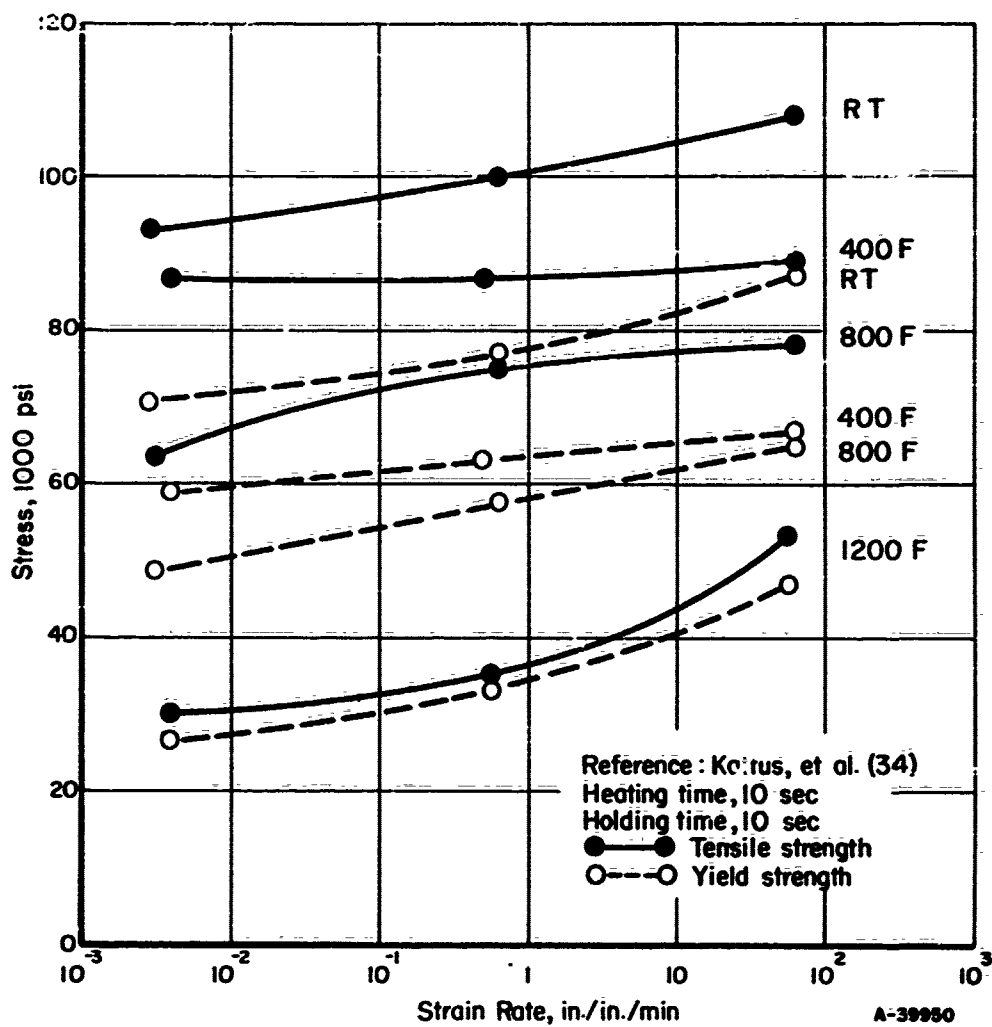


FIGURE 5. NORMALIZED AISI 4130 ALLOY STEEL SHEET,
 LONGITUDINAL SPECIMENS, 0.040-INCH THICK

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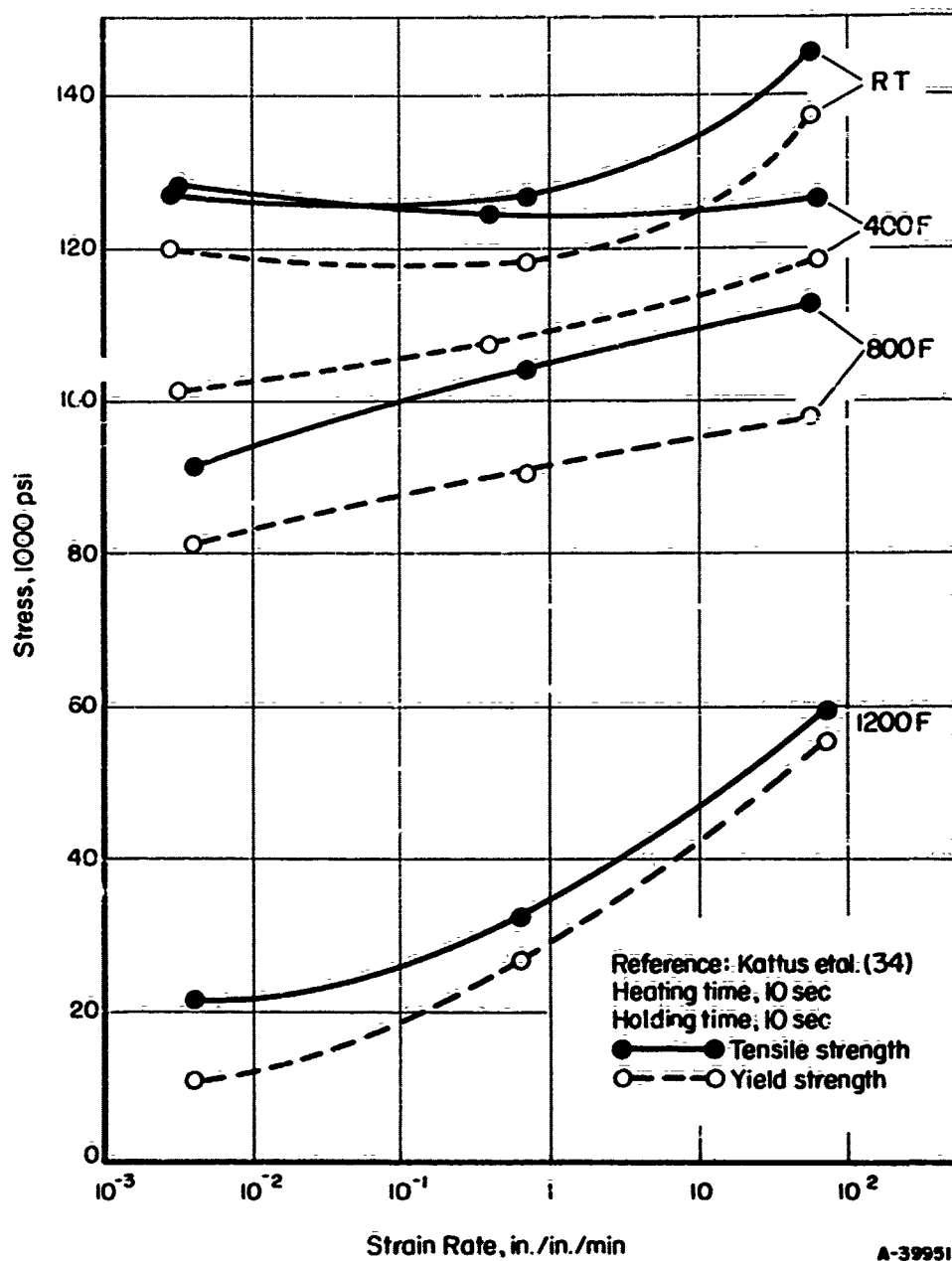


FIGURE 6. HARDENED AISI 4130 STEEL SHEET, LONGITUDINAL SPECIMENS, 0.040-INCH THICK
 (Austenitized 1570 F, oil quenched, tempered at 1000 F)

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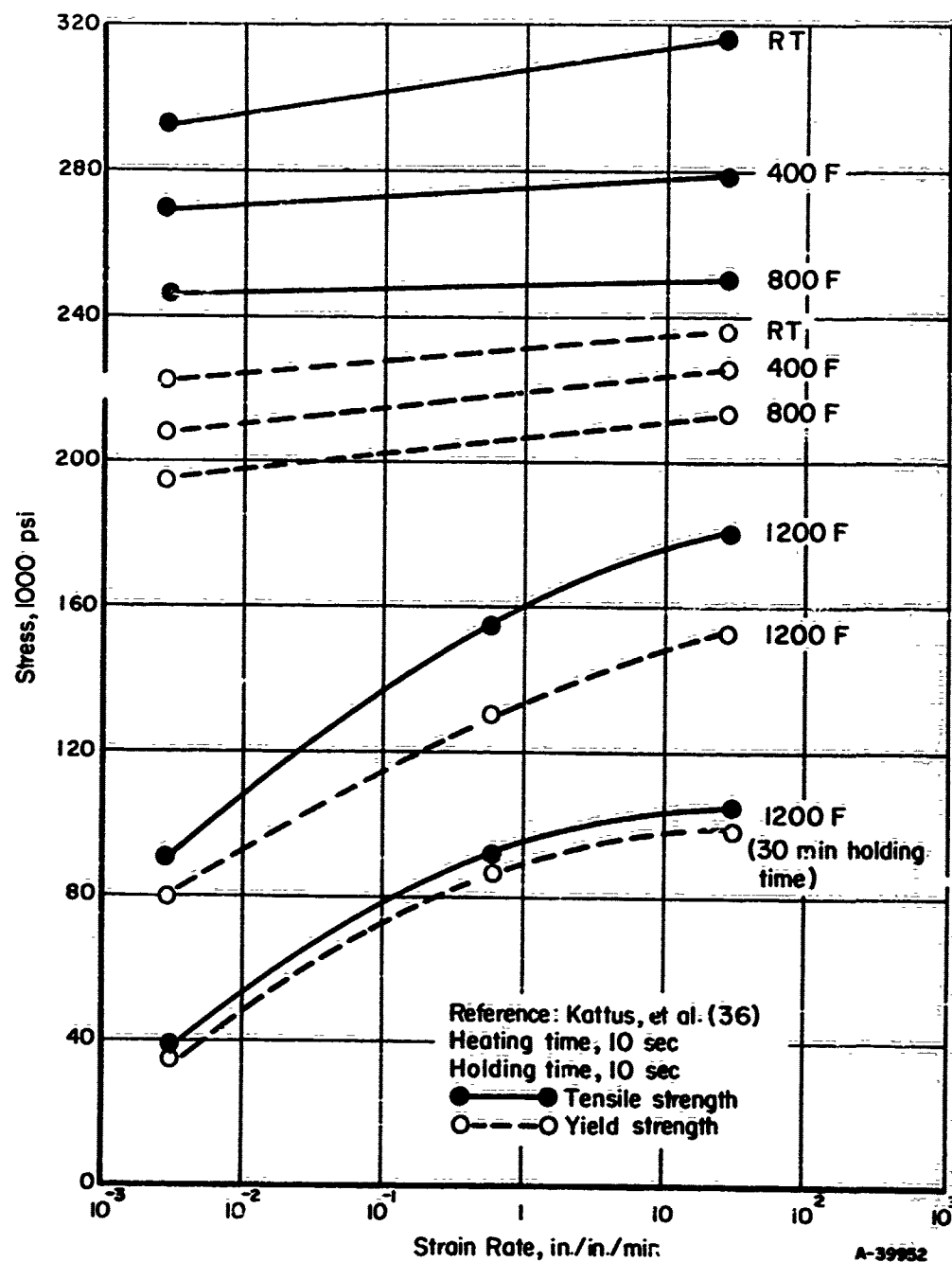


FIGURE 7. HEAT-TREATED THERMOLD J DIE STEEL SHEET, LONGITUDINAL SPECIMENS, 0.050-INCH THICK (Austenitized 1850 F 15 min, oil quenched, double tempered 950 F 2 hr)

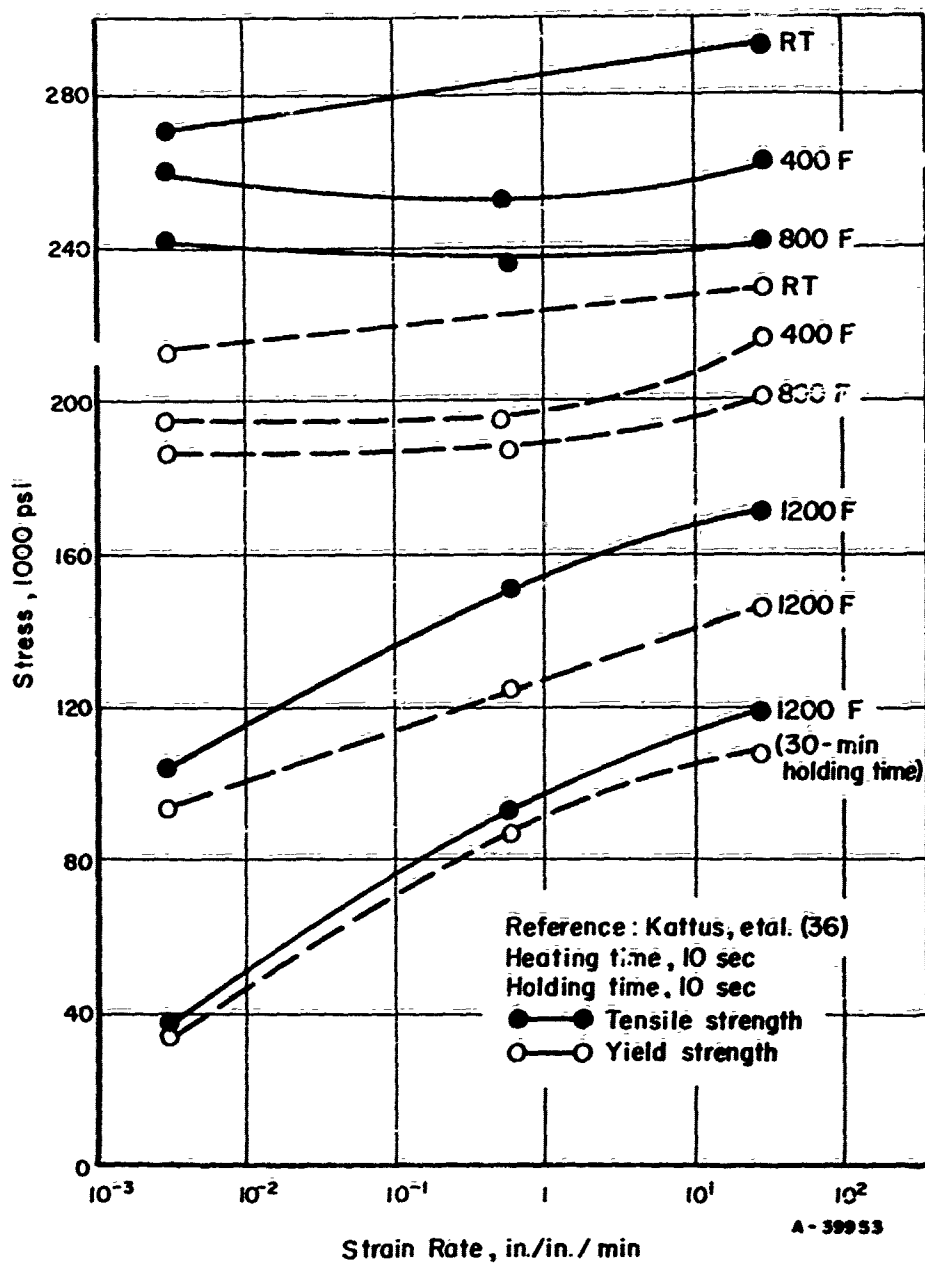


FIGURE 9. HEAT-TREATED PEERLESS-56 DIE STEEL SHEET,
 LONGITUDINAL SPECIMENS, 0.050-INCH THICK
 (Austenitized 1950 F 15 min, oil quenched,
 double tempered 950 F 2 hr)

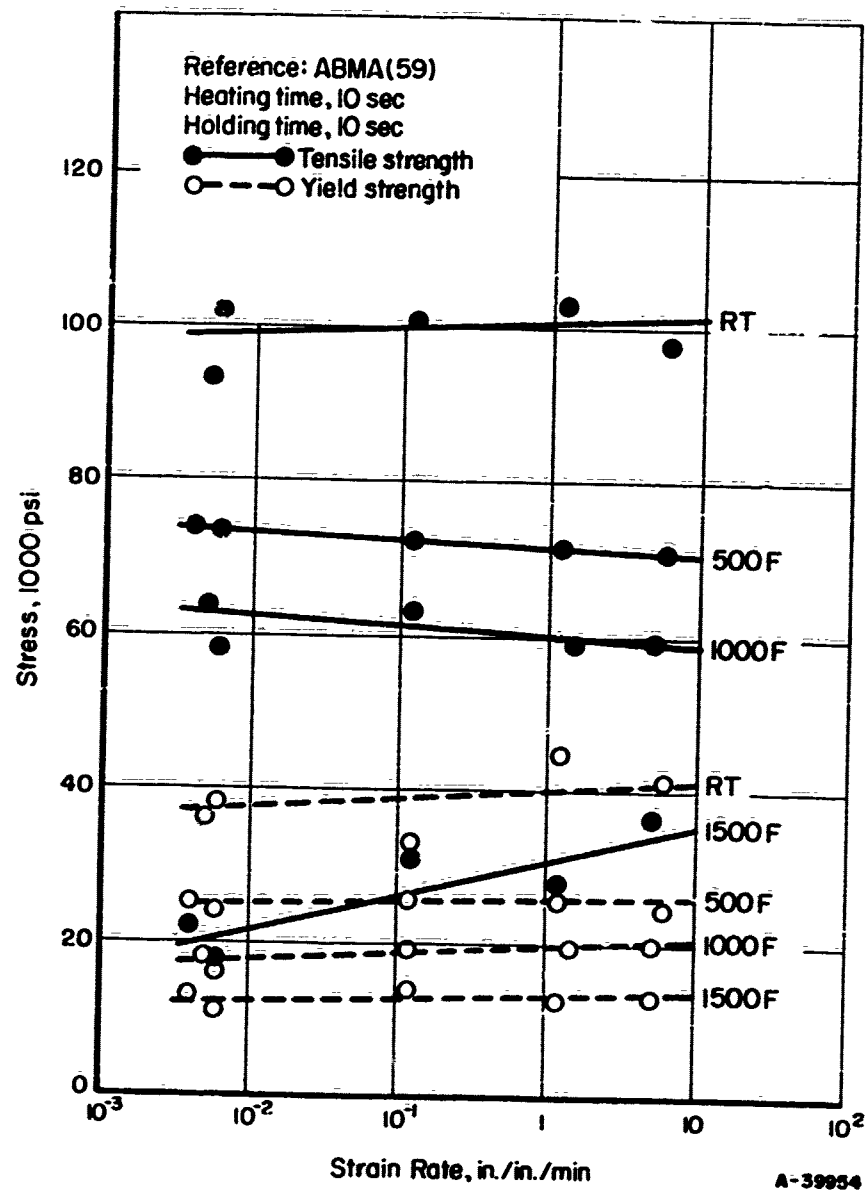


FIGURE 9. ANNEALED TYPE 301 STAINLESS STEEL SHEET,
LONGITUDINAL SPECIMENS

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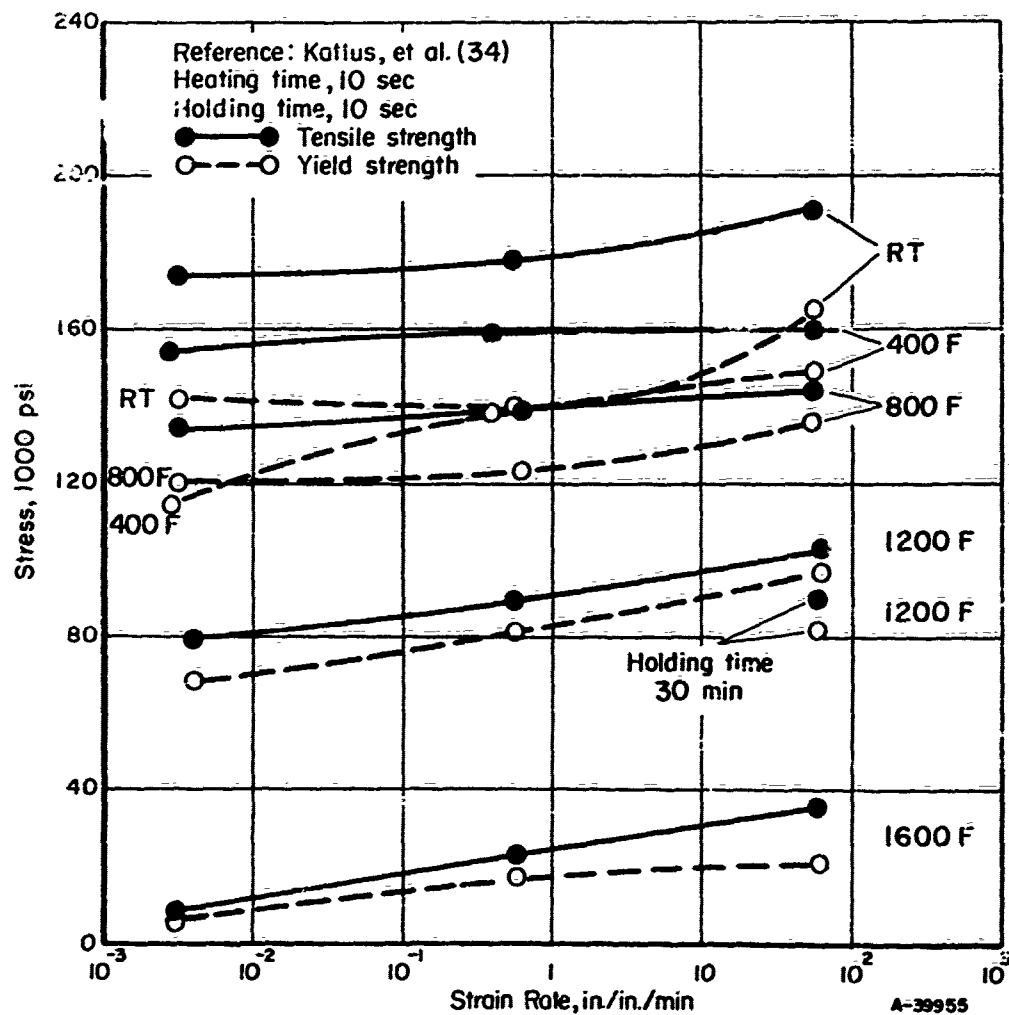


FIGURE 10. FULL-HARD TYPE 301 STAINLESS STEEL SHEET, LONGITUDINAL SPECIMENS, 0.040-INCH THICK

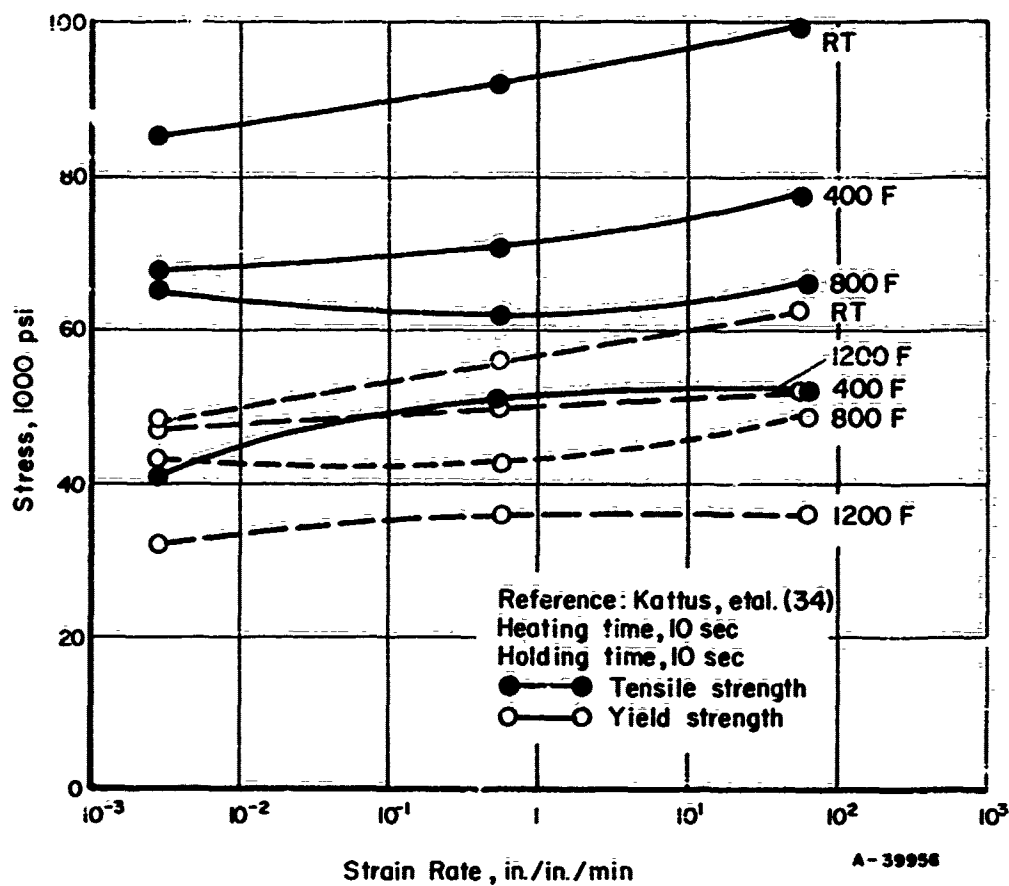


FIGURE 11. ANNEALED AND DULL COLD-ROLLED TYPE 321 STAINLESS STEEL SHEET, LONGITUDINAL SPECIMENS, 0.040-INCH THICK

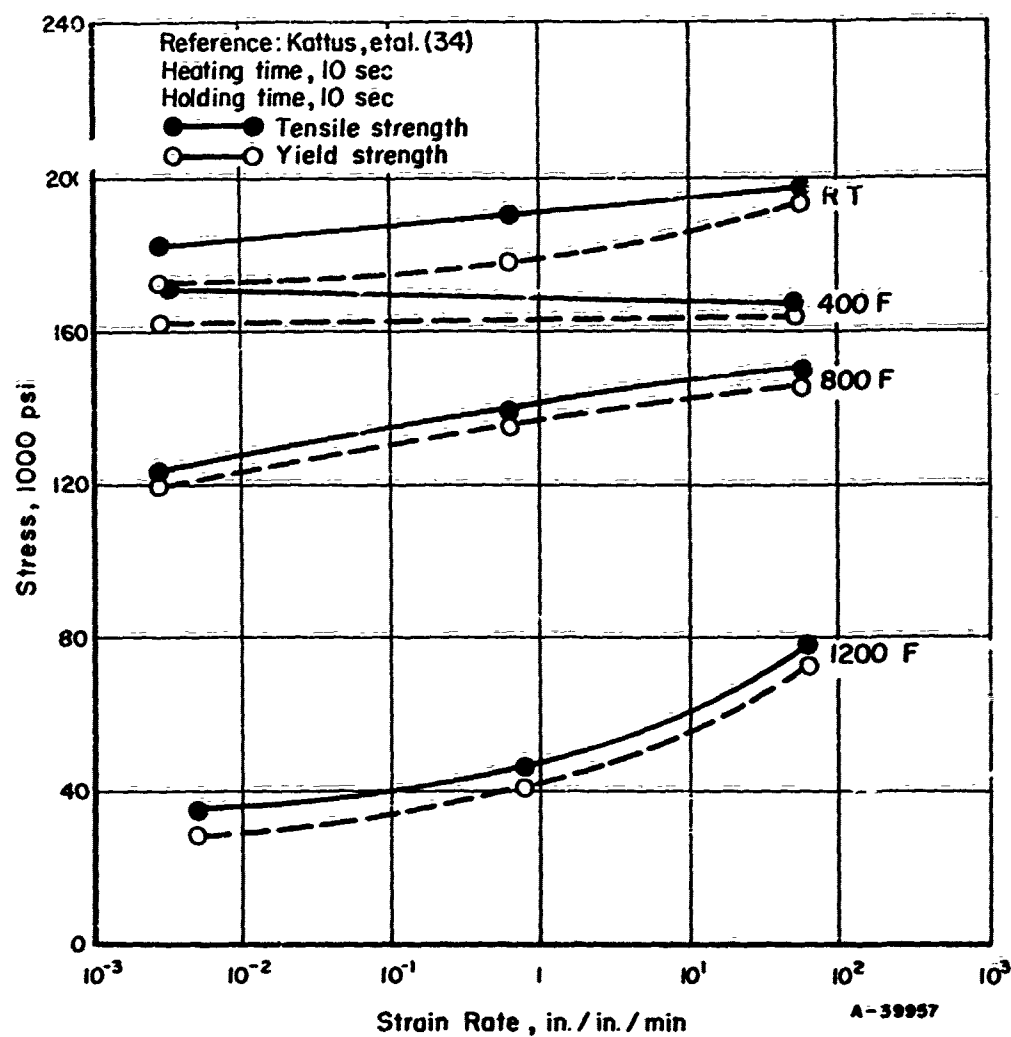


FIGURE 12. HARDENED 17-7 PH STAINLESS STEEL SHEET,
 TRANSVERSE SPECIMENS, 0.040-INCH THICK
 (1400 F 90 min, air cooled to RT and water
 quenched to 60 F, 1050 F 90 min, air cooled)

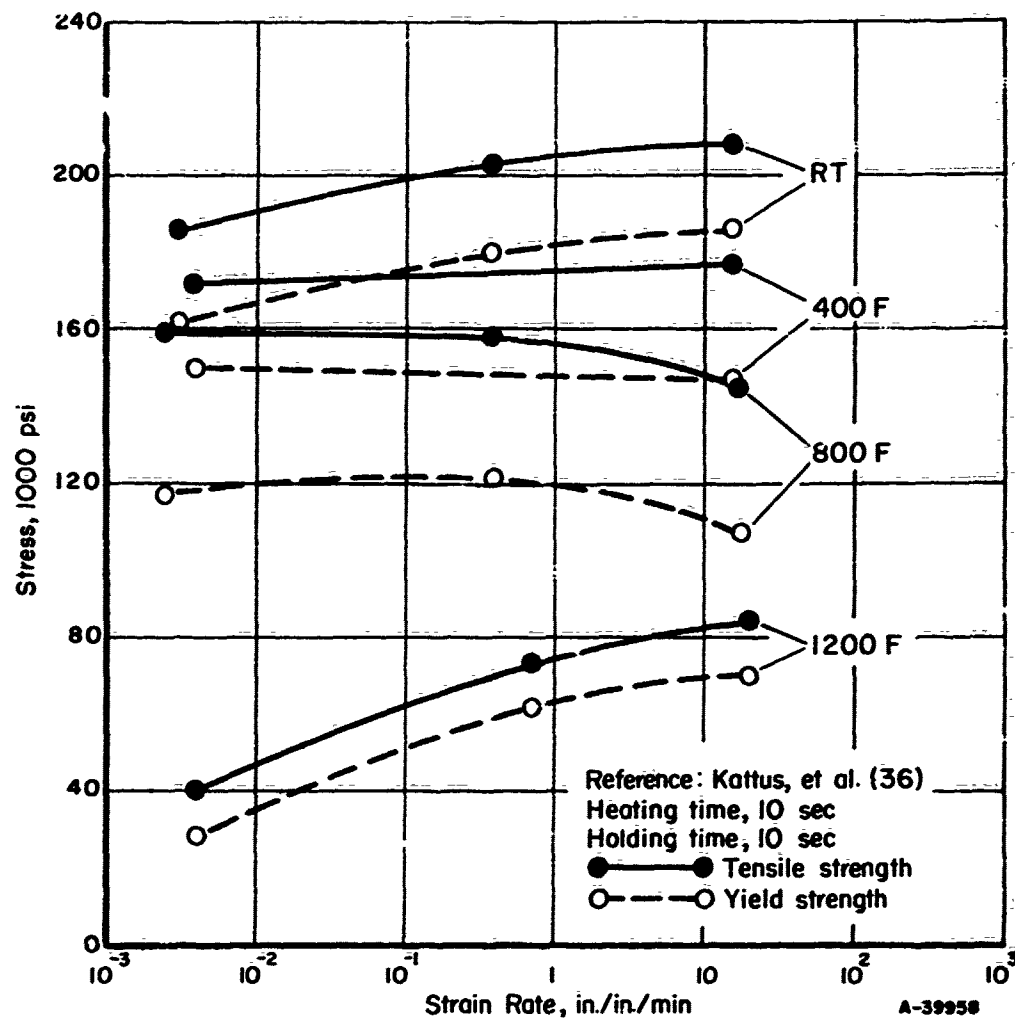


FIGURE 13. HARDENED AM-350 STAINLESS STEEL SHEET,
 LONGITUDINAL SPECIMENS, 0.040-INCH THICK
 (1725 F 30 min, water quenched, -100 F
 3 hr, 850 F 3 hr)

show the marked increase in strength to 1200 F resulting from cold working. Strengths of the full-hard alloy tended to increase as the strain rate increased. At 1200 F, the strengths were about the same for specimens tested at the slowest strain rate after holding at temperature for 10 seconds and 30 minutes. Tests at the fastest strain rate, however, resulted in lower strengths for the specimens held 30 minutes at temperature. Apparently this is characteristic of the material. On heating to 1600 F, recrystallization and grain growth occur, causing considerably lower strengths. This reaction apparently occurs during heating and within the 10-second holding time, because corresponding specimens that were held at temperature for 30 minutes had about the same strengths.

The data plotted in Figure 11 show the effect of increasing strain rates on the strength of annealed and dull rolled Type 321 stainless steel sheet. Within the range of temperatures employed, tests at room temperature showed the greatest increase in strength with increasing strain rates. Because of the thermal stability of this alloy, longer holding times at the elevated temperatures had no effect on the tensile properties.

Effects of increasing the strain rate when testing specimens of 17-7 PH stainless steel in the TH1050 condition are shown in Figure 12. Increase in strength with increase in the strain rate was noted for all temperatures except 400 F. The marked reduction in strength from the 800 to the 1200 F testing temperature is the result of the overtempering of these specimens at 1200 F.

Data for tensile tests on AM-350 stainless steel sheet are plotted in Figure 13 for three strain rates. With increased strain rates there was an increase in the room-temperature strength, a decrease in the 800 F strength, and an increase in the 1200 F strength. This steel was overaged at the 1200 F testing temperature.

Superalloys

The effects of increased strain rates on the yield strength of N-155 alloy sheet are shown in Figure 14. The effects of increased strain rates from room temperature to 1600 F are only nominal. At 1800 and 2000 F, the yield strengths tend to increase with increased strain rates. These specimens were held at temperature for 15 minutes before testing.

Values for tensile strength at increased strain rates for Unitemp 1753 bar in the solution-treated condition are shown in Figure 15. The marked decrease in strength at testing temperatures above 1450 F is noted in the figure. However, at testing temperatures of 1450, 1600, and 1750 F, the strengths were substantially increased by increasing the strain rate. At temperatures near the solution-treating temperature, increasing the strain rate had less effect on the strength. These specimens were heated to temperature over a 30-minute period and held at temperature for 30 minutes before testing.

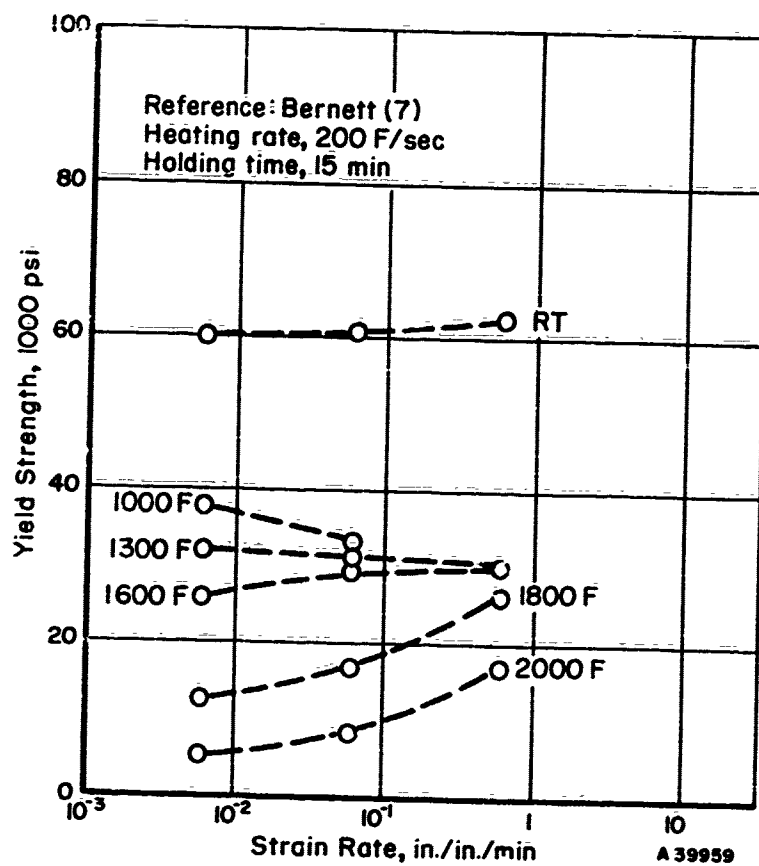


FIGURE 14. N-155 ALLOY SHEET MILL ANNEALED, LONGITUDINAL SPECIMENS, 0.063-INCH THICK

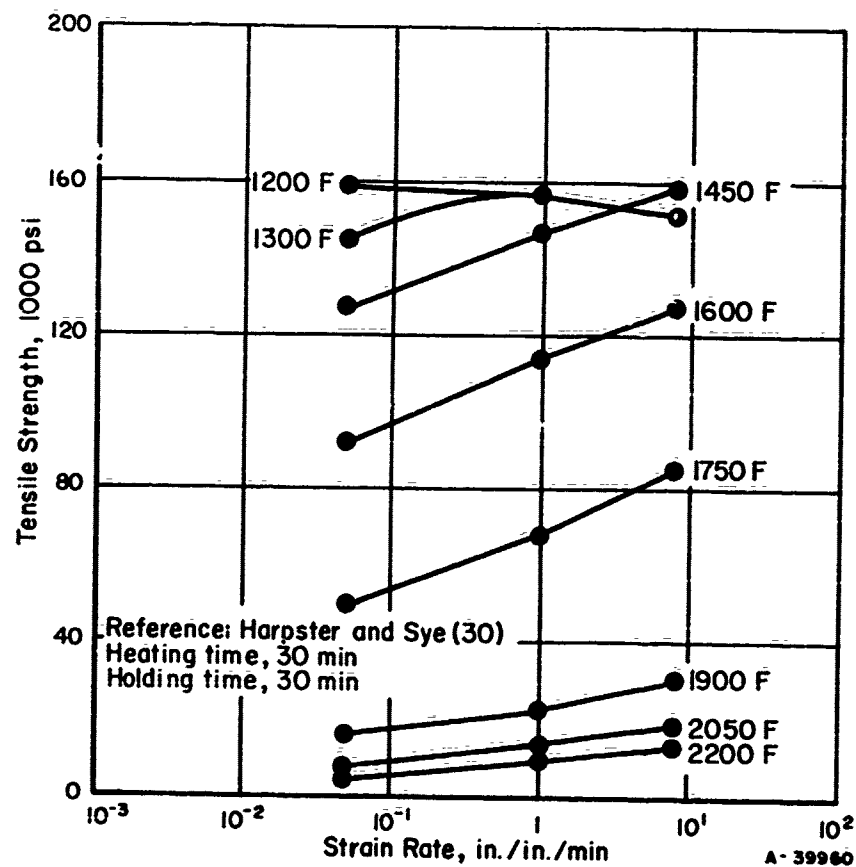


FIGURE 15. UNITEMP 1753 BAR SOLUTION TREATED
(2150 F 4 hr, air cooled)

Increasing the strain rate had little effect on the tensile properties of age hardened Inconel X sheet to 1200 F as shown in Figure 16. The tests made at 400 F showed a slight increase in strength with increased strain rates. However, this alloy is relatively stable to 1200 F. The tensile strength at 1600 F increased substantially with increased strain rates.

For Haynes Alloy 25 sheet, Figure 17, the effect of strain rate was most pronounced at room temperature and at 1600 F and above. In the room-temperature tests, the yield strength increased and the ultimate strength decreased at the highest strain rate. Increased holding times at testing temperature had little effect on the tensile properties because of the stability of this alloy.

Titanium Alloys

The effects of increasing the strain rate on the tensile properties of 5Al-2.5Sn titanium alloy in the annealed condition are shown in Figure 18. For this alloy, the yield and tensile strengths tend to increase as the strain rate is increased (except the tensile strength of the specimens tested at 400 F at the highest strain rate). This is a stable alpha alloy, and longer holding times had little effect on the properties.

Tensile properties of heat-treated 6Al-4V titanium alloy over a range of strain rates are shown in Figure 19. For this alloy, the strength tended to increase as the strain rate was increased over part or all of the strain-rate range. This alloy is relatively stable to the aging temperature.

Figure 20 illustrates the properties of annealed Ti-8Mn (alpha-beta) alloy sheet at increasing strain rates. It will be noted that the tensile properties were considerably lower at 1000 F than at 600 F. However, at 1000 F, increasing the strain rate resulted in a substantial increase in the tensile properties.

Data on the effect of increased strain rates on the beta titanium alloy, Ti-13V-11Cr-3Al, were available for the alloy in the annealed condition. These data are plotted in Figure 21. At room temperature, the strengths increase as the strain rate is increased. At 500 and 800 F the trend is reversed. The large decrease in tensile properties at normal testing speeds when increasing the testing temperature from 800 to 1200 F is shown in the figure. When the strain rates are increased for specimens tested in the range from 1200 to 1600 F, the tensile properties are increased substantially.

The marked increase in strength for testing temperatures from room temperature to 1200 F for the aged alloy, as compared to the annealed alloy, is also shown in Figure 21 for a strain rate of about 0.6 in./in./min. Data for other strain rates were not given. However, it appears that there would be little effect of strain rate on the strength to the aging temperature (900 F). It is expected that tests at 1200 F would show increased strengths with increasing strain rates. There is a marked drop in strength of the aged alloy when increasing the testing temperature from 1200 F to 1275 F. At 1500 F, the annealed and aged alloys have about the same strengths.

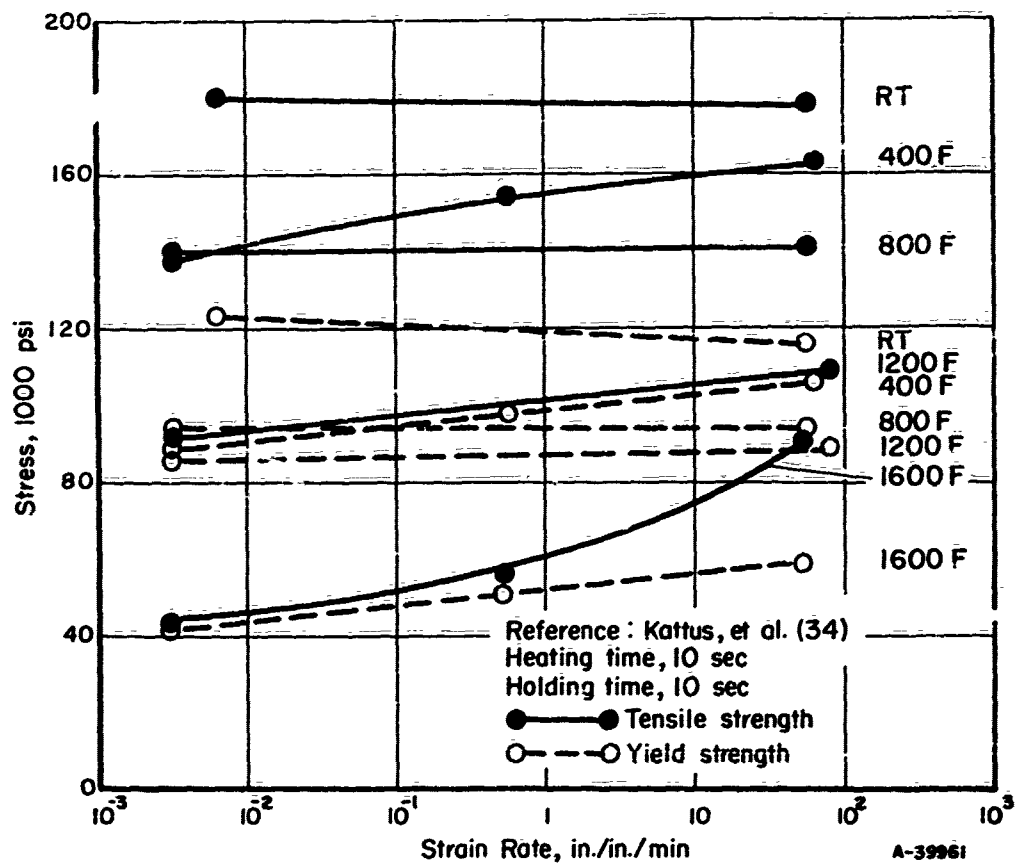


FIGURE 16. AGE-HARDENED INCONEL X SHEET, LONGITUDINAL SPECIMENS, 0.040-INCH THICK
 (Solution annealed then aged at 1300 F 20 hr, air cooled)

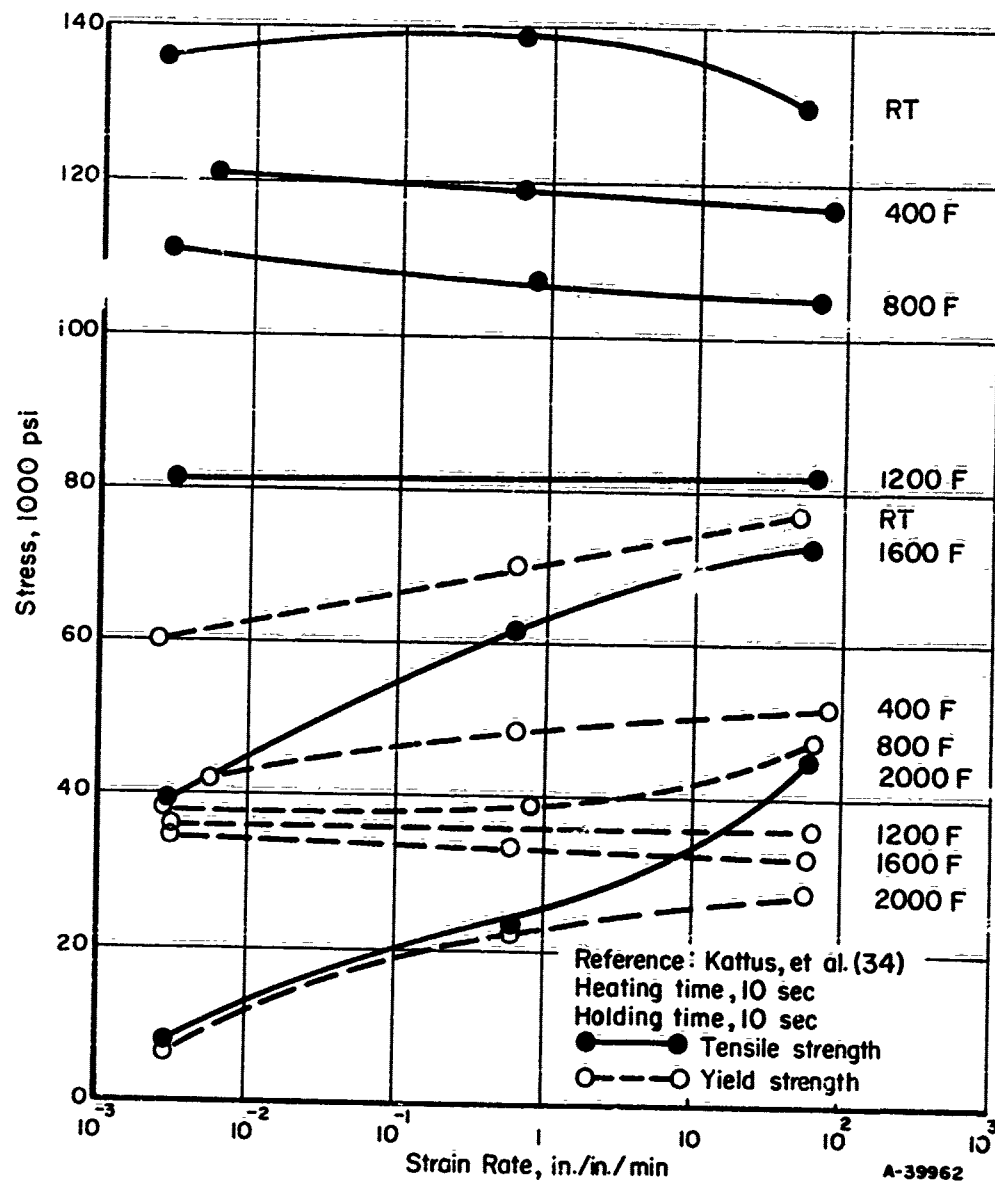


FIGURE 17. ANNEALED HAYNES ALLOY 25 (L-605) SHEET,
 TRANSVERSE SPECIMENS, 0.040-INCH THICK

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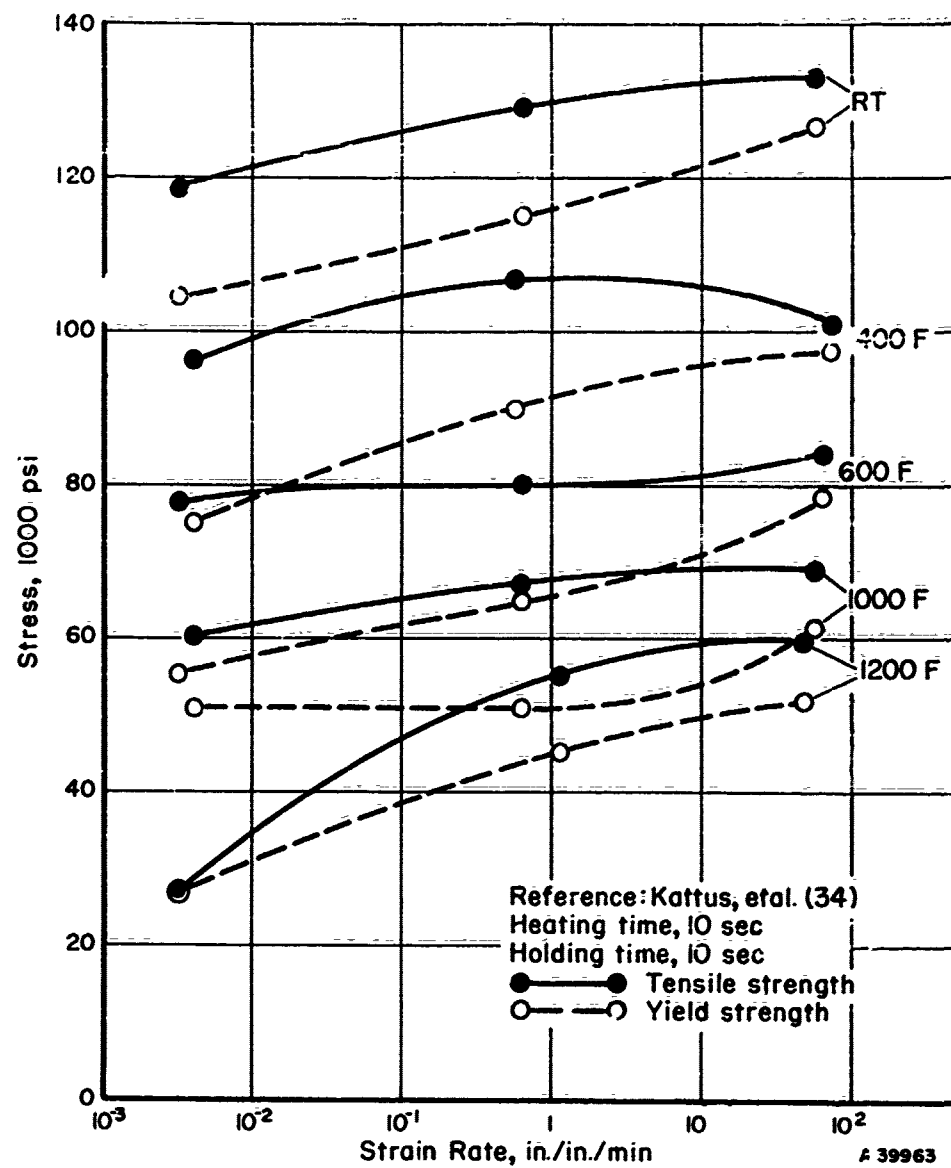


FIGURE 18. ANNEALED Ti-5Al-2.5Sn ALLOY SHEET,
 LONGITUDINAL SPECIMENS, 0.040-INCH THICK

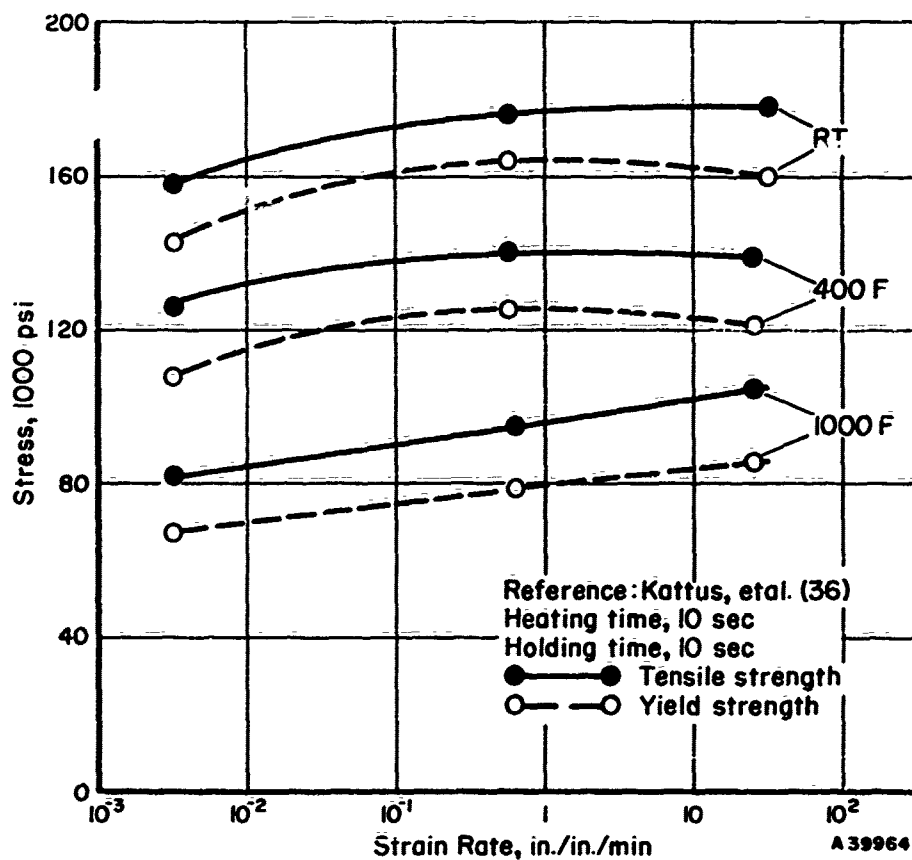


FIGURE 19. AGE-HARDENED Ti-6Al-4V ALLOY SHEET, LONGITUDINAL SPECIMENS, 0.040-INCH THICK
 (1750 F 10 min, water quenched, aged 1000 F 2 hr, air cooled)

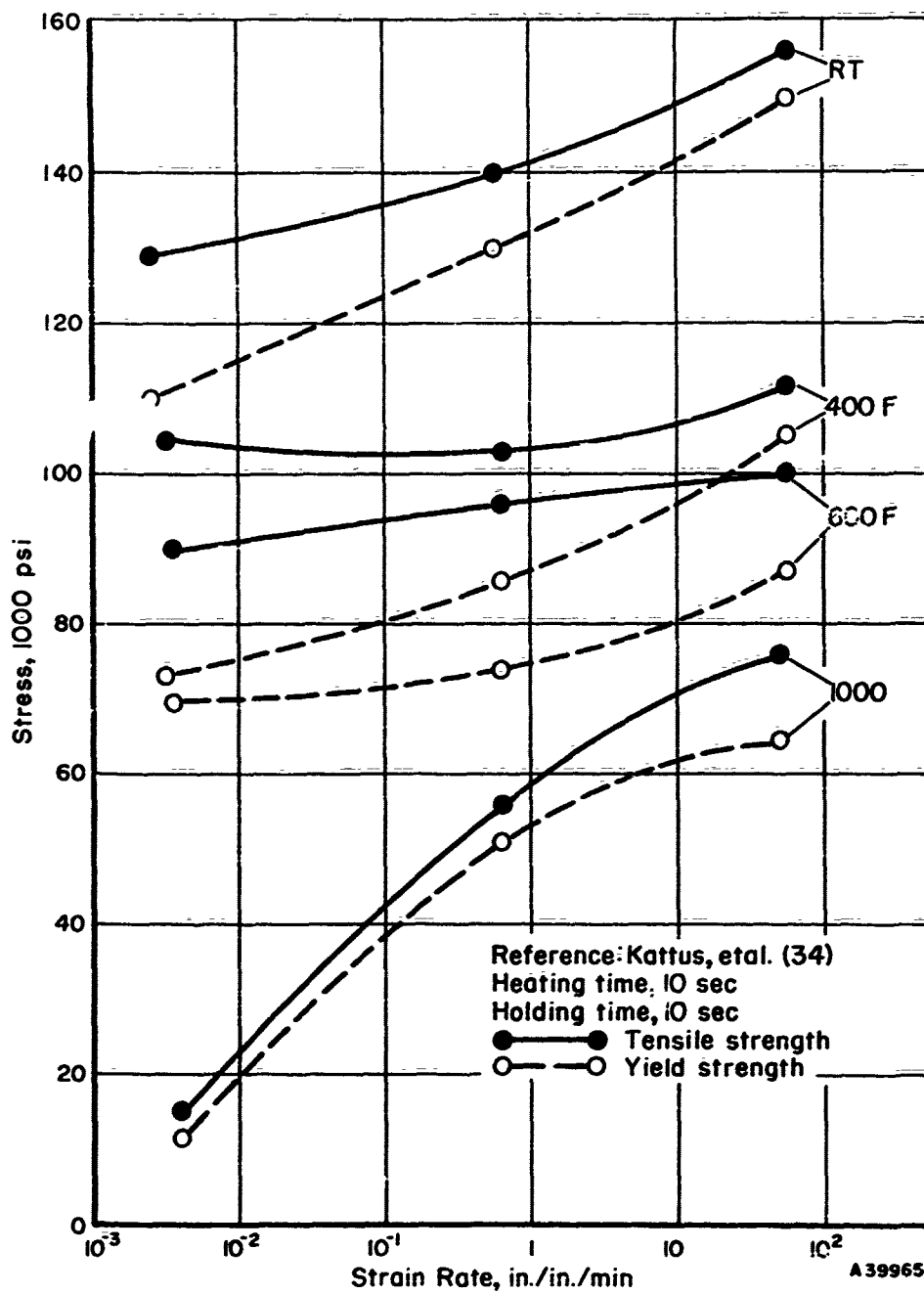


FIGURE 20. ANNEALED Ti-8Mn ALLOY SHEET, LONGITUDINAL SPECIMENS, 0.040-INCH THICK

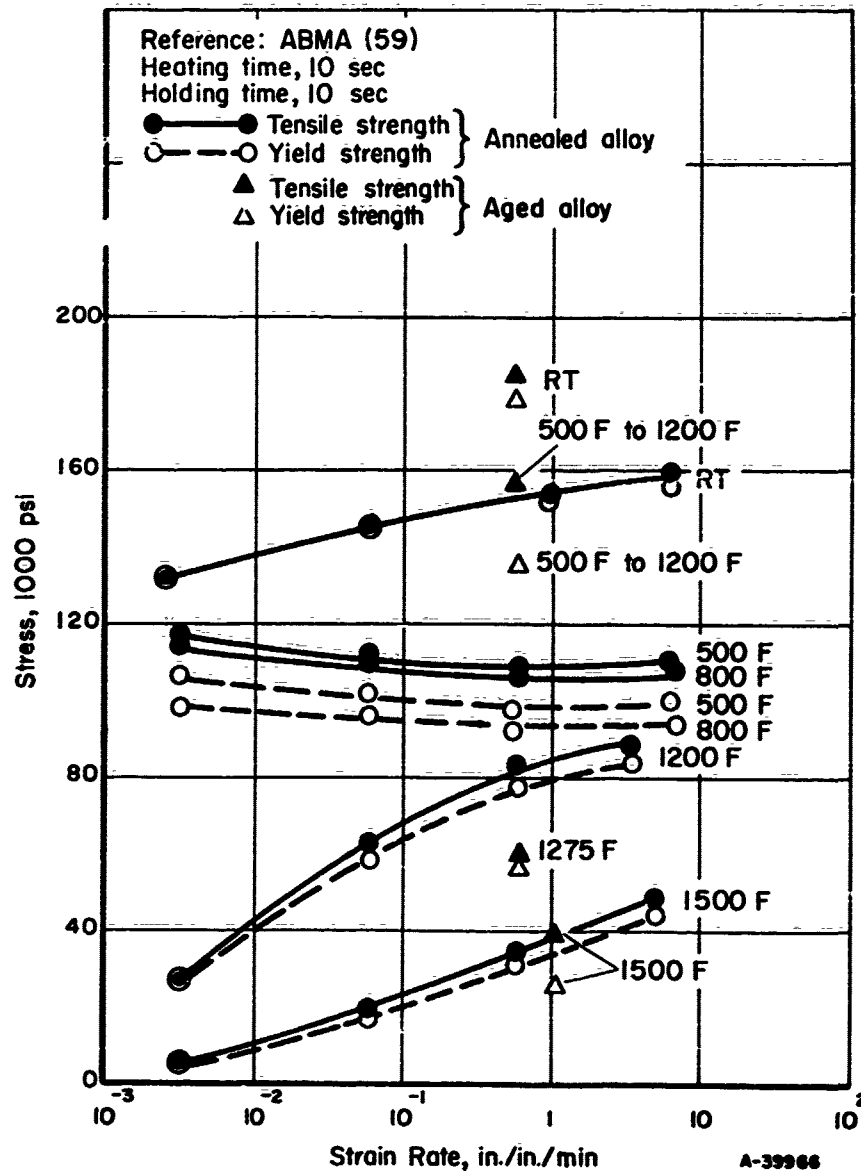


FIGURE 21. ANNEALED AND AGED 13V-11Cr-3Al TITANIUM ALLOY SHEET
(Aging Treatment: 900 F 50 hr)

BIBLIOGRAPHY

- (1) Alder, J. F., and Phillips, V. A., "The Effect of Strain Rate and Temperature on the Resistance of Aluminum, Copper, and Steel to Compression", Journal, Institute of Metals, 83, 80 (1954-1955).
- (2) Austin, A. L., and Steidel, R. F., Jr., "The Tensile Properties of Some Engineering Materials at High Rates of Strain", Proceedings, ASTM, 59, 1292-1306 (1959).
- (3) Baron, H. G., "Stress-Strain Curves of Some Metals and Alloys at Low Temperatures and High Rates of Strain", Journal, Iron and Steel Institute, 16, 354-365 (April, 1956).
- (4) Barranco, Joseph M., "Tensile Properties of Steel at Elevated Temperatures", Watervliet Arsenal Report No. WVT RR-5905 (AD 235500) (November, 1959).
- (5) Bechtold, J. H., "Strain Rate Effects in Tungsten", presented at AIME Fall Meeting, Philadelphia, October, 1955.
- (6) Bennett, E. C., "Short-Time, Elevated-Temperature Stress-Strain Behavior of Tensile, Compressive, and Column Members", Marquardt Corporation, WADC TR 59-484 (December, 1959).
- (7) Bennett, E. C., "Tensile and Short-Time Creep Properties of N-155 Alloy Steel". Prepared for presentation at the Annual Meeting of ASME at Atlantic City, New Jersey, November 29-December 4, 1959.
- (8) Campbell, J. D., "An Investigation of the Plastic Behavior of Metal Rods Subjected to Longitudinal Impact", Journal of Mechanics and Physics of Solids, 1, 113 (1953).
- (9) Carreker, R. P., and Guard, R. W., "Tensile Deformation of Molybdenum as a Function of Temperature and Strain Rate", Transactions, AIME, 206, 178 (February, 1956).
- (10) Carreker, R. P., and Guard, R. W., "Tensile Deformation of Molybdenum as a Function of Temperature and Strain Rate", WADC TR 55-111 (1955).
- (11) Catlin, J. P., and Wentz, W. W., "Effect of Strain Rate on the Mechanical Properties of Titanium Base Materials", WADC TR 53-71, Part 2 (February, 1955).
- (12) Clark, D. S., "The Behavior of Metals Under Dynamic Loading", Transactions, ASM, 46, 34-62 (1954).
- (13) Clark, D. S., "The Influence of Impact Velocity on the Tensile Characteristics of Some Aircraft Metals and Alloys", NACA, TN 868 (October, 1942).
- (14) Clark, D. S., and Datwyler, G., "Stress Relations Under Tension Impact Loading", Proceedings, ASTM, 38, Part II, 98-111 (1938).

- (15) Clark, D. S., and Duwez, P. E., "The Influence of Strain Rate on Some Tensile Properties of Steel", Proceedings, ASTM, 50, 560-575 (1950).
- (16) Clark, D. S., and Wood, D. S., "The Tensile Impact Properties of Some Metals and Alloys", Transactions, ASM, 42, 45-74 (1950).
- (17) "Conference on the Properties of Materials at High Rates of Strain", Proceedings of London Institute of Mechanical Engineers (April, 1957). Partial Contents:
 - "Deformation of Solids at High Rates of Strain", by A. H. Cottrell
 - "Yield Strength of Steel at an Extremely High Rate of Strain", by E. de L. Costello
 - "Experimental Techniques Developed in Investigations into High-Speed Yield in Brittle Fracture", by T. S. Robertson
 - "A Dynamic Tensile Testing Machine", by A. M. P. Brookes and J. L. Reddaway.
- (18) "Cooperative Study of the Effect of Strain on the Tensile Properties of Stainless Steel", Report of Subcommittee V on Mechanical Tests, Proceedings, ASTM, 44, 133-135 (1944).
- (19) DeSisto, T. S., "The True-Stress True-Strain Properties of Titanium and Titanium Alloys as a Function of Temperature and Strain Rate", Watertown Arsenal Technical Report, WAL TR 405.2/4 (March, 1960).
- (20) Duwez, P. E., Clark, D. S., and Wood, D. S., "Discussion of Energy Measurements in Tension Impact Measurements at the California Institute of Technology", NDRC Report A-217, Office of Scientific Research and Development, No. 1829.
- (21) Duwez, P. E., Clark, D. S., and Wood, D. S., "Dynamic Tests of the Tensile Properties of SAE 1020 Steels, Armco Iron and 17-ST Aluminum Alloy", NDRC Report A-182, Office of Scientific Research and Development, No. 1490.
- (22) Duwez, P. E., Clark, D. S., and Wood, D. S., "The Influence of Impact Velocity on the Tensile Properties of Plain Carbon Steel and of a Cast Armor Plate", NDRC Report A-154, Office of Scientific Research and Development, No. 1274.
- (23) Elam, C. F., "The Influence of Rate of Deformation on the Tensile Test with Special Reference to the Yield Point of Iron and Steel", Proceedings, Royal Society of London (England), 165, 568-592 (1938).
- (24) Fenn, R. W., Jr., and Gusack, J. A., "Effect of Strain Rate and Temperature on the Strength of Magnesium Alloys", Proceedings, ASTM, 58, 685-696 (1958).
- (25) Fields, D. S., Jr., and Backofen, W. A., "Temperature and Rate Dependence of Strain Hardening in the Aluminum Alloy 2024-O", Transactions, ASM, 51, 946 (1959).

- (26) Form, G. W., and Baldwin, W. M., Jr., "The Influence of Strain Rate and Temperature on the Ductility of Austenitic Stainless Steel", Transactions, ASM, 48, 474-485 (1956).
- (27) Fry, L. H., "Speed in Tension Testing and Its Influence on Yield Point Values", Proceedings, ASTM, 40, 625-636 (1940).
- (28) Fry, L. H., "Testing Speed Limitations for Committee A-1 Specifications for Steel", Proceedings, ASTM, 48, 1130-1132 (1948).
- (29) Griest, A. J., Sabroff, A. M., and Frost, P. S., "Effect of Strain Rate and Temperature on the Compressive Flow Stresses of Three Titanium Alloys", Transactions, ASM, 51, 935-944 (1959).
- (30) Carpenter, N. R., and Sye, J. H., "Some Effects of Temperature and Strain Rate on the Tensile Properties of Solution Treated Initemp 1753 Bar Stock", Universal-Cyclops Steel Corporation, Report No. 136 (June 30, 1959).
- (31) Jones, P. G., and Moore, H. F., "An Investigation of the Effect of Rate of Strain on the Results of Tension Tests of Metals", Proceedings, ASTM, 40, 610-624 (1940).
- (32) Kattus, J. R., "The effects of Strain Rate and of Temperature on Methods", presented before the Society of Aircraft Materials and Process Engineers (November 17, 1959).
- (33) Kattus, J. R., and Dotson, C. L., "Tensile, Fracture, and Short-Time Creep Properties of Aircraft-Structural Materials at Very High Temperatures after Rapid Heating", Southern Research Institute, WADC TR 55-391 (December, 1955).
- (34) Kattus, J. R., et al., "Tensile Properties of Aircraft-Structural Metals at Various Rates of Loading after Rapid Heating", Southern Research Institute, WADC TR 55-199, Part I (May, 1955), Part II (August, 1956), and Part III (July, 1957).
- (35) Kattus, J. R., et al., "Determination of the Mechanical Properties of Aircraft Structural Materials at Very High Temperatures after Rapid Heating", Southern Research Institute, WADC 57-649, Part I (January, 1958) and Part II (April, 1960).
- (36) Kattus, J. R., et al., "Tensile Properties of Aircraft Structural Metals at Various Rates of Loading after Rapid Heating", Southern Research Institute, WADC TR 58-440, Part I (October, 1958), and Part II (February, 1959).
- (37) Klier, E. P., and Gazzar, C. P., "Stress-Strain Properties of Selected Titanium Alloys", Proceedings, ASTM, 52, 1015-1028 (1959).
- (38) Klier, E. P., et al., "The Properties of Constructional Metals as a Function of Temperature and Strain Rate in Torsion", WADC TR 56-216 (1956).

- (39) Klinger, Richard F., "Tensile Properties of Some Aircraft Structural Materials at Various Rates of Loading", Proceedings, ASTM, 50, 1035-1050 (1950).
- (40) Krafft, J. M., "Note on Yield Strength Sensitivity for High Strength Steels", NRL Project 62R19-05, Technical Memo No. 85 (July 6, 1959).
- (41) Kramer, A., and Baldwin, W. M., Jr., "Carbide Precipitation and Brittleness in Austenitic Stainless Steel", Transactions, ASM, 50, 803-812 (1958).
- (42) Lubahn, J. D., "Derivation of Stress, Strain, Temperatures, Strain-Rate Relation for Plastic Deformation", Journal of Applied Mechanics, 14, ASME. 69, A229-A230 (1947).
- (43) Luster, D. R., Wentz, W. W., and Catlin, J. P., "Effect of Strain Rate on the Mechanical Properties of Titanium-Base Materials", WADC TR 53-71 (September, 1953).
- (44) Manjoine, M. J., "Effect of Rate of Strain on the Flow Stress of Gas Turbine Alloys at 1200 and 1500 F", Proceedings, ASTM, 50, 931-948 (1950).
- (45) Manjoine, M. J., "Influence of Rate of Strain and Temperature on Yield Stresses of Mild Steel", Transactions, ASME, 66, A-211-218 (1944).
- (46) Manjoine, M. J., and Nadai, A., "High-Speed Tension Tests at Elevated Temperatures", Proceedings, ASTM, 40, 822-837 (1940).
- (47) Manjoine, M. J., Wessel, E. T., and Pryle, W. H., "Constant Head Rate Testing Machine with Instantaneous Speed Change", ASTM Bulletin, No. 226 (December, 1957).
- (48) Mann, H. C., "High Velocity Tension Impact Tests", Proceedings, ASTM, 36, Part II, 85-97 (1936).
- (49) Martens, H. E., Button, D. D., Fischbach, D. B., and Jaffe, L. D., "Tensile and Creep Behavior of Graphites above 3000 F", California Institute of Technology, Jet Propulsion Laboratory, Progress Report 30-18 (October 15, 1959).
- (50) McDonald, R. J., Carlson, R. L., and Lankford, W. T., "The Effects of Strain Rate and Temperature on the Stress-Strain Relations of Deep-Drawing Steel", Proceedings, ASTM, 56, 604-720 (1956).
- (51) Miller, R. F., Smith, G. V., and Kehl, G. L., "Influence of Strain Rate on Strength and Type of Failure of Carbon-Molybdenum Steel at 850, 1000, and 1100 F", Transactions, ASM, 31, 817-848 (1943).
- (52) Moore, A. A., "The Effect of Speed of Testing on Magnesium-Base Alloys", Proceedings, ASTM, 48, 1133-1138 (1948).
- (53) Nadai, A., and Manjoine, M. J., "High Speed Tension Tests at Elevated Temperatures", Transactions, ASME, 63, A77-A91 (1941).

- (54) Paca, F. B., "The Response of Materials to Dynamic Loads", Technical Report No. 1643-TR, Army Engineering Research and Development Labs, Fort Belvoir, Va. (July 20, 1960).
- (55) Parker, E. R., and Ferguson, C., "The Effect of Strain Rate on the Tensile Impact Strength of Some Metals", Transactions, ASM, 30, 68 (1942).
- (56) Powell, G. W., Marshal, E. R., and Backofen, W. A., "Strain Hardening of Austenitic Stainless Steel", Transactions, ASM, 50, 478-496 (1958).
- (57) Preston, J. B., and Kattus, J. R., "Determination of the Mechanical Properties of Aircraft-Structural Materials at Very High Temperatures after Rapid Heating", WADC TR 57-649, Part II, Southern Research Institute (April, 1960).
- (58) Rinehart, John A., "The Behavior of Metal Under High and Rapidly Applied Stresses of Short Duration", Navord Report 1183 (September 27, 1949).
- (59) "Short Time Elevated-Temperature Mechanical Properties of Metals Under Various Conditions of Heat Treatment, Heating, Exposure Time, and Loading", Contract No. DA-01-009-ORD-491, Summary Report to Army Ballistic Missile Agency, Southern Research Institute (July 17, 1959).
- (60) Short-Time High-Temperature Testing, American Society for Metals (1958).
- (61) Simmons, W. F., "Short-Time Creep and Tension Testing of Aircraft and Missile Materials After Rapid Heating", presented before the Society of Aircraft Materials and Process Engineers (November 17, 1959).
- (62) Steidel, R. F., Jr., and Makerov, C. E., "The Tensile Properties of Some Engineering Materials at Moderate Rates of Strain", ASTM Bulletin, No. 247, pp 57-64 (July, 1960).
- (63) Tankins, E. S., and Maddin, R., "Effect of Grain Size, Strain Rate, and Temperature on the Yield Point of Columbium", Transactions, AIME, 215, (1959).
- (64) Tardif, H. P., "A Review of CARDE Activities in the Field of High Rates of Loading", CARDE Technical Memorandum No. 253/59 (July, 1959).
- (65) Tardif, H. P., and Erickson, Wm., "Mechanical Properties of Metals Under Dynamic Loading", CARDE Technical Memorandum No. 192/58 (April, 1958).
- (66) Taylor, G. I., "The Testing of Materials at High Rates of Loading", Journal, Institution of Civil Engineers, 26, 486-519 (October, 1946).
- (67) Trozera, T. A., Sherby, O. D., and Dorn, J. E., "Effect of Strain Rate and Temperature on the Plastic Deformation of High Purity Aluminum", Transactions, ASM, 49, 173-188 (1957).

- (68) Weinstein, D., Sinclair, G. M., and Wert, C. A., "The Strain Rate and Temperature Dependence of the Ductile to Brittle Transition in Molybdenum Subjected to Torsional Loading", University of Illinois, T. & A.M. Report 156, WADC TN 59-2 (December, 1959).
- (69) Winlock, J., "The Influence of the Rate of Deformation on the Tensile Properties of Some Plain Carbon Sheet Steels", Transactions, AIME, 197, 797-803 (1953).
- (70) Wong, A. K., and Gazza, G., "Hot Hardness and Tensile Properties of Stainless Steel Type 304, Titanium Alloy Ti-150A, and SAE 4140 Steel at 300 and 600 F", Watertown Arsenal Laboratories, Technical Report 116/2 (July, 1959).
- (71) Work, C. E., and Dolan, T. J., "The Influence of Strain Rate and Temperature on the Strength and Ductility of Mild Steel in Torsion", Proceedings, ASTM, 53, 611-626 (1953).
- (72) Work, C. E., and Dolan, T. J., "The Influence of Temperature and Rate on the Properties of Metals in Torsion", Engineering Experiment Station Bulletin Series No. 420, University of Illinois (November, 1953).
- (73) Yokobori, T., "Delayed Yield and Strain Rate and Temperature Dependence of Yield Point in Iron", Journal of Applied Physics, 25 (5), 593-594 (1954).
- (74) Zaikov, M. A., "Influence of the Rate of Deformation on the Strength of Carbon Steel at High Temperatures", Zhurnal Tekhnicheskoi Fiziki, 19 (6), 711-721 (June, 1949).
- (75) Zener, C., and Hollomon, J. H., "Effect of Strain Rate Upon the Plastic Flow of Steel", Journal of Applied Physics, 15, 22-32 (January, 1944).

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131	Review of Recent Developments in the Technology of High-Strength Stainless Steels, October 1961
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138	Review of Recent Developments in the Technology of Beryllium, November 16, 1961
139	Review of Recent Developments in the Technology of Tungsten, November 24, 1961
140	Review of Recent Developments in Metals Joining, December 6, 1961
141	The Emittance of Chromium, Columbium, Molybdenum, Tantalum, and Tungsten, December 10, 1961

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